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METHOD OF USING LOW BANDWIDTH SENSOR FOR MEASURING HIGH FREQUENCY AC MODULATION AMPLITUDE

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TECHNICAL FIELD OF THE INVENTION

[0001] The present invention is directed, in general, to output power control for optical data transmission sources and, more specifically, to output power monitoring configurations for data transmission lasers.

BACKGROUND OF THE INVENTION

[0002] Data transmission over an optical medium such as an optical fiber typically requires use of a laser classified by the limit imposed on output power (and the corresponding danger associated with use of such output power), with many systems employing, for instance, a Class 2 laser. Accordingly, the output power of lasers employed must satisfy stringent eye safety requirements and equally stringent requirements defined by the transmission protocol (e.g., Ethernet, fiber channel, etc.).

[0003] Conventional optical power control schemes employ a p-type/intrinsic/n-type (PIN) semiconductor light detection monitor diode and a partially reflective lens to monitor the output of a vertical cavity surface emitting

laser (VCSEL) or other light source. A small fraction of the light emitted by the laser is reflected to the PIN diode, which converts the light to an electrical current sensed by a transimpedance amplifier for conversion into a voltage. The voltage representative of the reflected light is compared against a reference voltage and an error signal generated on the basis of that comparison is employed to servo the VCSEL light output power to desired level.

[0004] High bandwidth or full bandwidth monitor diodes add significant expense to the cost of an optical transmission source. In addition, precision alignment of the light source, partially reflective lens, and monitor diode is required for high bandwidth monitor diodes.

[0005] There is, therefore, a need in the art for a less expensive monitor diode configuration.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, wherein like numbers designate like objects, and in which:

[0007] FIGURE 1 depicts a computer implementing prediction and control of optical modulation amplitude and/or extinction ratio for an optical sub-assembly therein according to one embodiment of the present invention;

[0008] FIGURE 2 is a high level flowchart illustrating a process of controlling optical modulation amplitude and/or extinction ratio for an optical sub-assembly according to one embodiment of the present invention;

[0009] FIGURE 3A is a high level flowchart illustrating a process for determining average power without utilizing feedback from an optical monitor according to one embodiment of the present invention;

[0010] FIGURE 3B depicts a low bandwidth diode optical monitor configuration for determining average output power according to another embodiment of the present invention; and

[0011] FIGURE 4A through 4E illustrate simulation results for operation of a low-bandwidth diode optical monitor configuration for determining average output power according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0012] To address the above-discussed deficiencies of the prior art, it is a primary object of the present invention to provide, for use in an optical subassembly for network transmission of data over an optical fiber from a computer, determination of output power of light emitted from a data transmission light source based upon forward voltage, forward current, ambient temperature and a factor specific to the manner in which the light source is mounted. Output power is determined with sufficient accuracy to control operation of the data transmission light source for compliance with eye safety and transmission protocol requirements without use of a complex lens and monitor diode.

[0013] The foregoing has outlined rather broadly the features and technical advantages of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features and advantages of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art will appreciate that they may readily use the conception and the specific embodiment disclosed as a basis for modifying or designing

other structures for carrying out the same purposes of the present invention. Those skilled in the art will also realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

[0014] Before undertaking the detailed description below, it may be advantageous to set forth definitions of certain words or phrases used throughout this patent document: the terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation; the term "or" is inclusive, meaning and/or; the phrases "associated with" and "associated therewith," as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, or the like; and the term "controller" means any device, system or part thereof that controls at least one operation, whether such a device is implemented in hardware, firmware, software or some combination of at least two of the same. It should be noted that the functionality associated with any particular controller might be centralized or distributed, whether locally or remotely. Definitions for

certain words and phrases are provided throughout this patent document, and those of ordinary skill in the art will understand that such definitions apply in many, if not most, instances to prior as well as future uses of such defined words and phrases.

[0015] FIGURES 1 through 4E, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the present invention may be implemented in any suitably arranged device.

[0016] FIGURE 1 depicts a computer implementing prediction and control of optical modulation amplitude and/or extinction ratio for an optical sub-assembly therein according to one embodiment of the present invention. Those skilled in the art will recognize that the full construction and operation of a mobile computer is not depicted and described. Instead, for simplicity and clarity, only so much of a mobile computer as is unique to the present invention or necessary for an understanding of the present invention is depicted or described.

[0017] Computer 100 includes a processor 101, main memory 102, and bridges 103 and 104 enabling the processor 101 to interface with other system elements. Processor 101 employs a memory controller host or "north bridge" 103 to interface with main memory 102 and graphics units (not shown). Processor 101 employs an interface controller host or "south bridge" 104, coupled to the north bridge 103 by a hub interface, to interface with other devices over standard, general-purpose buses such as a Peripheral Component Interconnect (PCI) bus.

[0018] In the present invention, south bridge 104 is coupled (using, for instance, a card mounted within a PCI bus slot) to an optical sub-assembly (OSA) 105 including an optical transceiver and a controller (not shown) providing a network connection over an optical medium, such as an Ethernet network connection over optical fiber(s). Control of the optical transmission power for optical sub-assembly 105 is based on optical modulation amplitude or extinction ratio in the manner described in further detail below.

[0019] In describing the scheme for control over extinction ratio according to the present invention, the following values are employed: P_o represents the instantaneous VCSEL output power; P_{avg} represents the time-averaged

(low pass filtered) value of output power P_o; I represents VCSEL current; I_1 represents logical "1" ("on") level current and I_0 represents logical "0" ("off") level current, which typically is not zero; I_{avg} represents average VCSEL current calculated from $I_{avg}=(I_1+I_0)/2$; I_{th} represents threshold current; I_{mod} represents modulation current calculated from $I_{mod}=I_1-I_0$; η represents slope efficiency; $ER=10\log(P_1/P_0)$ represents extinction ratio; $OMA=(P_1-P_0)$ represents optical modulation amplitude, more commonly employed in current control systems than ER; and T_n denotes sampling time.

[0020] The power output of a VCSEL is given by:

$$P_o=(I-I_{th})\eta\text{, and}$$

$$P_{avg}=(I_{avg}-I_{th})\eta\,.$$

Assuming that two samples of average power $P_{avg}(T_1)$ and $P_{avg}(T_2)$ are taken, and further assuming that the threshold current I_{th} and slope efficiency η remain constant across those measurements, the expression above for average power may be written as:

$$P_{avg}(T_1)=(I_{avg}(T_1)-I_{th})\eta\text{, and}$$

$$P_{avg}(T_2)=(I_{avg}(T_2)-I_{th})\eta\,.$$

Solving these equations for the two desired variables:

$$I_{th} = \frac{P_{avg}(T_1) \cdot I_{avg}(T_2) - P_{avg}(T_2) \cdot I_{avg}(T_1)}{P_{avg}(T_1) - P_{avg}(T_2)}, \tag{1}$$

$$\eta = \frac{P_{avg}(T_1) - P_{avg}(T_2)}{I_{avg}(T_1) - I_{avg}(T_2)}. \tag{2}$$

The average power and average current will depend on the logical data value being transmitted at times T_1 and T_2.

[0021] The exemplary embodiment of the present invention utilizes equations (1) and (2) above in real time control of both the average power and extinction ratio. Since average power monitoring is being performed in real time, with the results fed back to control the bias current I_{bias} and modulation current I_{mod}, by using two appropriate samples of average power one parameter (e.g., slope efficiency) may be very closely approximated while the other parameter (threshold current in this example) is precisely known from the two measurements.

[0022] FIGURE 2 is a high level flowchart illustrating a process of controlling optical modulation amplitude and/or extinction ratio for an optical sub-assembly according to one embodiment of the present invention. In the example depicted and described, average power is controlled by varying I_1 and extinction ratio is controlled by varying I_{mod}. In an alternative embodiment, the dependence of

optical modulation amplitude on the modulation current I_{mod} could be determined from the equations given above, and controlled in lieu of extinction ratio.

[0023] The process 200 begins by initialization of $I_1=I_{1,min}$, $I_{mod}=0$ and $I_{th}=I_{th,min}$ (step 201). Next, and average output power sample $P_{avg}(N)$ is determined (step 202) from, for example, electrical characteristics of the VCSEL or the output signal from a low bandwidth monitor diode, as described in further detail below. The average power measurement $P_{avg}(N)$ is compared to a target value P_{target} to determine if the average power measurement is less than the target (step 203). If so, the present logical 1 level current I_1 (the maximum current driven through the VCSEL) is incremented (step 204), provided the maximum operating limit set for that parameter $I_{1,max}$ (e.g., the maximum current that the VCSEL can tolerate) has not previously been reached. If not, however, the average power measurement $P_{avg}(N)$ is compared to a target value P_{target} to determine if the average power measurement exceeds or is greater than the target (step 205). If so, the logical 1 level current I_1 is decremented (step 206), provided the

minimum operating limit set for that parameter $I_{1,min}$ has not previously been reached.

[0024] If the average power measurement $P_{avg}(N)$ is neither less than nor greater than the target (i.e., the average power measurement $P_{avg}(N)$ equals the target value), the extinction ratio may be presumed to have been set to an acceptable value in a previous iteration of the process such that no further adjustment is required, and the process returns to step 202. Note that this may also be the case when the average power measurement $P_{avg}(N)$ does not equal the target value, but the logical 1 level current I_1 cannot be adjusted (i.e., I_1 has already reached $I_{1,max}$ or $I_{1,min}$).

[0025] On the other hand, if the logical 1 level current I_1 is incremented or decremented, the modulation current I_{mod} is altered to achieve (in this example) the desired extinction ratio (step 207). For this purpose, it may be noted that:

$$ER = 10 \cdot \log_{10}\left(\frac{P_1}{P_0}\right),$$

$$\Rightarrow ER = 10 \cdot \log_{10}\left(\frac{I_1(N) - I_{th}(N)}{I_1(N) - I_{mod}(N) - I_{th}(N)}\right)$$

so that, using the desired extinction ratio value and the threshold current estimate from the previous loop cycle, the modulation current may be set by:

$$I_{mod}(N) \approx (1-10^{-ER/10})(I_1(N)-I_{th}(N-1)).$$

[0026] Finally, before proceeding with the next loop iteration (i.e., returning to step 202), the estimated threshold current I_{th} is calculated for use in the next iteration (step 208).

[0027] FIGURE 3A is a high level flowchart illustrating a process for determining average power without utilizing feedback from an optical monitor according to one embodiment of the present invention. As noted above, the VCSEL light output power may be monitored directly utilizing a lens and PIN diode. Alternatively, however, the average power measurement $P_{avg}(N)$ required for estimating and controlling optical modulation amplitude or extinction ratio as described above may be determined based on conservation of power and temperature measurements.

[0028] While a temperature sensor such as a diode, a thermocouple, or the like may be integrally formed with the VCSEL for use in measuring the die temperature, the forward voltage V_f of a VCSEL has a well-known dependence on temperature. Accordingly, the die temperature for the VCSEL may

be determined by monitoring the forward voltage V_f, which is commonly already measured. The die temperature is also dependent on total power dissipated in the VCSEL and the temperature coefficient of the optical sub-assembly (OSA), such that VCSEL light power may be expressed as:

$$\text{Power(optical)} = \text{P(electrical)} - \frac{\text{T(VCSEL)} - \text{T(ambient)}}{\theta_{ja}},$$

where T(VCSEL) is a function of the VCSEL forward voltage, T(ambient) is the ambient temperature surrounding the VCSEL integrated circuit, measured by a temperature sensor, and θ_{ja} (where "ja" represents junction-to-ambient, as opposed to junction-to-case and case-to-ambient) is a value specific to the manner in which the VCSEL is mounted and may be determined for a specific design and fabrication process.

[0029] The expression above for power may be rewritten as:

$$\text{Power(optical)} = V_f(\text{VCSEL}) \Box I_f(\text{VCSEL}) - \frac{\text{fn}(V_f(\text{VCSEL})) - \text{T(ambient)}}{\theta_{ja}}.$$

The forward current I_f, which for most VCSELs has a small and predictable variation dependent on forward voltage/ temperature, may be measured using a series resistance, calculated, or determined. Similarly, the temperature

T(VCSEL) may be calculated or determined from a lookup table based on the forward voltage.

[0030] Accordingly, in one embodiment of the present invention illustrated by process 300, whenever an output power measurement is initiated (step 301), the forward voltage V_f of the VCSEL and ambient temperature T(ambient) around the VCSEL are measured (step 302). The forward current I_f and die temperature T(VCSEL) are determined from the measured forward voltage (step 303), either by calculation or using a look-up as described above. The optical power is then calculated (step 304), and the process becomes idle until another power measurement is required (step 305).

[0031] The embodiment of FIGURE 3A avoids the need for a complex lens to reflect part of the transmitted light onto a monitor diode used to control the average power of the transmitted light, reducing mechanical and optical design complexity, assembly process complexity, and cost. Potentially more accurate power information is available, without the necessity for detailed knowledge of the packed design or VCSEL characteristics.

[0032] FIGURE 3B depicts a low bandwidth diode optical monitor configuration for determining average output power

according to another embodiment of the present invention. As noted above, a common configuration 306 for measuring output power involves passing the light emitted by VCSEL 307 through a complex lens 308 passing most of the light through to the transmission medium (not shown) but reflecting a portion onto a monitor diode 309.

[0033] In current systems, the PIN monitor diode 309 is typically either slow and used to control average power only, causing extinction ratio and optical modulation amplitude to vary with operating conditions, or very expensive full bandwidth PIN diodes that more accurately monitor transmitted light. In the present invention, low bandwidth PIN diodes are employed to collect the power measurements required to estimate and control extinction ratio or optical modulation amplitude as described above. Such low bandwidth PIN diodes are less expensive

[0034] Accordingly, monitor diode 309 is an inexpensive PIN diode with low bandwidth, employed to extract information about light modulation including average output power measurements employed to control both average power P_{avg} and extinction ratio or optical modulation amplitude. As long as the monitor diode has sufficient bandwidth to overlap the lower end of the transmitted spectrum (with a

bandwidth of about 10% frequency of the emitted light being sufficient), the output current from the monitor diode 309 will reach the peak value for long run lengths (e.g., long runs of consecutive logical 1's). Therefore, by monitoring the peak-to-peak value of the output from monitor diode 309 using a peak detector, optical modulation amplitude may be estimated. In other words, the output eye of the monitor diode 309 will be completely closed due to intersymbol interference (ISI), but the peak-to-peak value is a true (and direct) representation of the VCSEL output optical modulation amplitude.

[0035] FIGURE 4A through 4E illustrate simulation results for operation of a low-bandwidth diode optical monitor configuration for determining average output power according to one embodiment of the present invention. FIGURE 4A depicts the equivalent circuit 400 employed for simulation, in which the signal source 401 generating 1.25 giga-bits per second (Gbps) data at various amplitudes is coupled to a low pass filter (R_0 and C_0) approximating the bandwidth of an inexpensive, low frequency PIN sensor diode. The output of the filter is coupled by alternating current (AC) coupling capacitor C_2 to peak detectors 402-403 detecting upper and lower signal peaks for the output of the low pass filter.

[0036] FIGURE 4B is the output eye diagram for the sensor, using a 1 volt peak-to-peak input signal at 1.25 Gbps and a 50 megaHertz (MHz) low pass filter. A 30-50 MHz low pass filter is preferable, since above 50 MHz the response becomes a function of bandwidth. The eye in FIGURE 4B is completely closed, but the peak-to-peak amplitude of the eye is close to the peak-to-peak amplitude of the transmitted signal, even though the sensor bandwidth is less than a tenth of the data rate. FIGURE 4C depicts the same data plotted in FIGURE 4B superimposed with peak detector outputs with an exponential decay at a rate of 100 kilo-Hertz (KHz), a decay rate selected to be much lower than the low frequency content of the input data.

[0037] FIGURE 4D illustrates results of a parametric simulation varying 1.25 Gbps input data amplitude over four different levels (0.25 V, 0.5V, 0.75 V and 1.0 V) and sensor bandwidth over 16 linear steps (from 7.8125 MHz to 62.5 MHz). The results suggest that the peak-to-peak output of a low frequency sensor is a good representation of the peak-to-peak input signal amplitude. As the sensor bandwidth is varied, the peak-to-peak output goes through two fairly linear slopes: at very low sensor bandwidths (less than $1/40^{th}$ of the data rate), the sensitivity is higher than at higher sensor bandwidth, resulting from

roll-off in the spectrum of the input signal. Once the input spectrum begins to fall, signal power in the combined spectrum (both signal and low pass filter) reduces at twice the rate, resulting from roll-off due to the low pass filter nature of the signal and the high pass filter nature of the signal. This roll-off is depicted in FIGURE 4E, where signal LPF-1 (the middle sloped line and the horizontal line connecting that line to the ordinate) covers the signal spectrum such that power rolls off due to a single pole (the low pass filter) as sensor bandwidth is reduced, while signal LPF-2 (bordering the cross-hatched area) covers the signal spectrum such that power rolls off due to two poles (one due to the sensor low pass filter and the other due to the high pass filter of the signal spectrum, depicted by darker lines).

[0038] The present invention allows precise control over average power output for a light source in a data transmission system based on power measurements, while estimating and controlling either extinction ratio or optical modulation amplitude. In one embodiment, the power parameters required for such control may be derived from temperature and forward voltage measurements. In an alternative embodiment, peak-to-peak measurements from a

low bandwidth monitor diode directly indicate optical modulation amplitude.

[0039] Although the present invention has been described in detail, those skilled in the art will understand that various changes, substitutions, variations, enhancements, nuances, gradations, lesser forms, alterations, revisions, improvements and knock-offs of the invention disclosed herein may be made without departing from the spirit and scope of the invention in its broadest form.